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Comments Submitted to the Department of Transportation (DOT)
National Highway Traffic Safety Administration (NHTSA)

in response to

February 7, 2002 Request for Comments :
National Academy of Science Study and
Future Fuel Economy Improvements, Model Years 2005 – 2010

[Docket No. 2002-11419]

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Abstract

Sonex Research, Inc. submits that it is feasible to improve fuel economy of light trucks 25% to 30% by the demonstrable Sonex Combustion System (SCS) for in-cylinder control of ignition and combustion. The SCS improvement in combustion overcomes the "weight-fuel mileage-safety" falsehood; therefore, the automotive industry could focus on increased fuel economy without sacrificing safety. A national policy that challenges the automotive industry to cost-effectively achieve the 25% to 30% improvement in fuel economy necessitates an attainable technology push. The result of such a policy would be the automotive industry's best dream … American consumers willing to pay full price and wait for delivery as production ramps up on a new generation of vehicles. This would provide a boost to the Nation that had not been anticipated when the CAFÉ follow-on became an issue.

About Sonex

Sonex Research, Inc. ("Sonex" or the "Company") is a small business located in Annapolis, Maryland. Sonex is engaged in the research, development and commercialization of a patented proprietary technology (the "Sonex Combustion System" or "SCS") which improves the combustion of fuel in engines through design modification of the pistons in four-stroke engines or the cylinder heads in two-stroke engines. The Sonex engineering and technological team is headed by the Company's Founder and Chief Executive Officer, Dr. Andrew A. Pouring, a former Professor of Aerospace Engineering and Chairman of the Department of Aerospace Engineering at the U.S. Naval Academy.

The SCS process is applicable to: (1) classical diesels as a means to reduce soot by 45% with no fuel consumption increase and, if used in conjunction with high levels of exhaust gas recirculation (EGR), to reduce oxides of nitrogen (NO_x) and soot with a slight fuel consumption increase that is still less than other alternatives for reducing emissions as required by EPA regulations; and (2) gasoline combustion based on compression ignition and high rates of heat release ("lean burn-fast burn") at gasoline engine peak cylinder pressures to improve fuel economy 25% to 30% while reducing emissions to EPA Tier II criteria.

The SCS is operable in a single-cylinder research engine in the fully equipped Sonex laboratory in Annapolis. In spite of persistent efforts by Sonex for nearly two years to "get our word" to the right people in the U.S. automotive industry, the potential of the SCS is being virtually ignored.

Sonex also has successfully established a heavy fuel engine (HFE) technology baseline by applying its SCS technology to the conversion of lightweight, spark-ignited, two-stroke, gasoline engines to start and operate on kerosene-based heavy fuels such as JP-5, JP-8 and D-2 diesel for military applications. HFE conversions have been performed for a variety of spark-ignited, two-stroke engines used in unmanned aerial vehicles (UAVs). Sonex is also developing a process for the conversion of spark-ignited, four-stroke, gasoline engines to compression ignition of heavy fuels.

Objective

The CAFÉ follow-on for light trucks Model Years 2005 - 2010 should establish a national policy to achieve increased fuel mileage, assure cleaner air and provide improved vehicle safety.

Sonex submits that it would be in the national interest for a CAFÉ follow-on for light trucks to incorporate an attainable technology push to achieve a near term 25% to 30% increase in fuel economy and Tier II emissions compliance. Feasibility of this objective is demonstrable today on the basis of in-production Japanese direct injection gasoline (GDI) engine technologies, the availability of low sulfur gasoline in 2006 (as set by the EPA), and the lean burn-fast burn compression ignition-combustion process enabled by the patented Sonex piston-based innovation.

Background

First generation GDI engine technology is capable of improving fuel mileage by at least 15% by virtue of the elimination of the throttle and the associated pumping losses. Over 1 million Mitsubishi vehicles have been produced in Japan since 1996 that are powered by GDI engines having displacements from 1.1 to 4.5 liters. The U.S. Department of Energy (DOE) has tested a Mitsubishi, 5-passenger sedan in the 2,700-pound class (similar in size to the Volvo S40 and Ford Focus sold in the U.S.) and measured 53 mpg in the EPA highway test[1]. However, GDI engine technology inherently has a NOx exhaust problem that precludes introduction of these vehicles in the U.S.

All automobile manufacturers are familiar with the benefits of the GDI engine as well as the challenging NOx problem. Engine researchers know the key to solving the GDI NOx problem is to replace its spark-ignited, mixed-mode (lean) combustion with a leaner mixture employing homogeneous, compression ignition and controlled, high rate heat release combustion. In a June 2001 *Scientific American* article (pp. 91 - 95) entitled “A Low-Pollution Engine Solution,” Mr. Tom Asmus, Senior Research Executive for Daimler-Chrysler Corporation, referred to such a process as homogenous-charge, compression ignition (HCCI). Unfortunately, HCCI as envisioned and reported in the literature does not work across the engine speed and load characteristics needed in an automotive application.

[1] Cole, R.L., Poola, R.B., Sekar, R., “Exhaust Emissions of a Vehicle with a Gasoline Direct Injection Engine”, SAE Paper 982605, 1998.

Technical Feasibility of a Sonex Lean Burn–Fast Burn Engine

Sonex has developed a paradigm shifting, high rate of heat release combustion system for direct injected engines that can provide the benefits of HCCI and solve the speed-load problem. As a result, the SCS for in-cylinder control of ignition and combustion can deliver better unthrottled fuel economy than today's GDI engines and should exhibit a NOx reduction of over 80% that will enable meeting EPA Tier II criteria using low sulfur gasoline. The demonstrable SCS is based on a patented piston design. Sonex U.S. Patent No. 5,862,788 (January 1999) and others address a combustion chamber for direct injection, compression ignition engines that improves the combustion process through a combination of chemical and fluid dynamic effects.

The SCS piston designs integrate cavities called microchambers (MCs) which form a segmented ring around the piston bowl (see Figure 1 at the end of this document). The MCs are connected to the piston bowl by vents. The MCs and vents are aligned to each spray from the fuel injector in the combustion chamber of the direct injection engine. The MCs function as chemical reactors, producing highly active chemical species from a small fraction of the fuel-air charge delivered via the vents. In a low compression ratio direct injected SCS engine, the chemical species are produced, conserved and the remainder expelled via the vents on the next air intake stroke to fumigate the air. On the compression stroke the recycled chemical species increase in temperature and become highly effective autoignition aids that enable controllable, low compression ratio, autoignition at high air-fuel ratios as a function of fuel injection timing. As a result, the SCS engine operates under complete control over the full range of speed and load required in any automotive application.

Sonex accomplishments can be appreciated by the data from the SCS single cylinder laboratory engine operating on *diesel* fuel per the attached figures: Figure 2 - NOx less than 80 parts per million (ppm) over the Tier II test range compared to over 500 ppm for all other types of combustion; Figure 3 - requisite power output at high air-fuel ratios (lean) between 45:1 (highway cruise power level) to 25:1 (heavy acceleration power level); Figure 4 - low fuel consumption rates (approximates a diesel); and Figure 5 - very low smoke and particulates. Significantly, Figure 6 shows that SCS operates at cylinder pressures consistent with light weight automotive gasoline engine construction to assure economical production. These data are significant advances over any known lean burn-fast burn gasoline or classical diesel combustion process.

The Sonex no-spark, homogeneous combustion process is a lean burn-fast burn process that demonstrates *fully controllable* autoignition by using properly timed injection from idle to full load. The chemical species seeded into the unthrottled air on the intake stroke together with timed direct injection enable low compression ratio autoignition and homogeneous combustion. Homogeneous combustion is evidenced by high rate, single-phase combustion at all speeds and loads yielding low NOx and soot emissions. In Figure 7 at full load and a nominal 2000 rpm with compression ratio of 12.5:1, the start of injection was set at 20 degrees before top dead center (TDC) resulting in a peak single phase heat release at 13 degrees after TDC, of 37.47 cal/degree. The width of the base is only about 5 degrees of crank angle. In Figure 8 at 1/4 load, the peak single-phase heat release is at 18 degrees after TDC while start of injection is still at 20 degrees before TDC. Notably, there is no diffusive phase evident in the combustion analyzer results. The single-phase heat release results in these figures are typical of the full engine map and insure high-speed operation. A major benefit of the very short heat release is a significant reduction in heat losses that yields an overall improvement in fuel economy of 25% to 30%. A spark-ignited GDI engine will not exhibit these advantages.

Preliminary operation in a single-cylinder engine of the SCS on regular grade gasoline demonstrated feasibility by confirming compression ignition and high rates of heat release compared to classical performance of spark ignited gasoline. Sonex plans to achieve full characterization of the SCS on gasoline. Characterization can be accomplished in six months and in a second phase the results transferred to an existing automotive engine for laboratory evaluation. This development strategy is the subject of a Sonex proposal to the DOE in its Automotive Technology Program.

The SCS operating on military kerosene-based heavy fuels in an adapted Subaru gasoline automotive engine for a priority unmanned helicopter development is the subject of a Sonex proposal to the Department of Defense (DoD). Sonex has been advised by DoD that its proposal has tentatively been selected for a contract award. A variant of this engine platform could be used in the second phase of an award under the DOE proposal to expedite development of a laboratory SCS GDI engine.

Impact on the Industry

The automotive industry is well known for its cost-of-manufacture sensitivity. Development of near term SCS piston-based engines of all sizes could be adaptations of current production engines. The higher cost of the SCS piston to achieve the potential of these engines would be minimal compared to any other near term alternative that achieves a 25% to 30% fuel mileage increase and can "pay for itself." The SCS based reduction in fuel consumption of 25% to 30% can be applied to any GDI vehicle concept, thereby preserving vehicle weight that should be allocated for achieving safer designs. The SCS also would be beneficial for the evolution to safer, high fuel mileage U.S. produced hybrid powered vehicles.

In fact, the White House's May 2001 National Energy Policy Report (pp. 4-10) addresses hybrids as follows: "Although promising, it may be many years before hybrids become a substantial part of the automobile fleet." Significant improvements in fuel mileage by virtue of SCS pistons could provide the basis of cost competitive engines for conventional vehicles and could also enhance the fuel mileage of hybrids. Ultimately, the evolution of U.S. produced hybrid powered vehicles would be accelerated since an improvement in fuel economy of 25% to 30% provides opportunity for tradeoff of vehicle weight versus power.

Furthermore, the internal combustion engine is not going to be displaced by highly publicized hydrogen fuel cells in the near future. For example, a Ford Focus powered by a 90hp fuel cell system gained nearly 1,100 pounds (in curb weight) with hydrogen stored in two 5,000 psi tanks in the trunk. Leaders of the automotive industry have written that they see such fuel cells as viable and infrastructure supported in 15 to 25 years. The internal combustion engine cannot be written off because there simply isn't a near-term alternative. Consequently, the Sonex paradigm shift in combustion technology that provides significantly increased fuel economy and lowered emissions will assure production of the internal combustion engine far into the future.

Responses to Selected Questions from Docket No. 2002-11419, Section III – "Issues in Developing a Proposal for MY2005-2010"

1. <u>Could CAFÉ standards be modified so that manufacturers are encouraged to achieve improved fuel economy through application of technology instead of through downsizing and down weighting?</u>

   In providing a response to this question, Sonex takes note of the introductory remark of Docket question #9 regarding taking technological risks in setting light truck CAFÉ standards. Sonex presumes the wealth of information submitted by interested parties will take NHSTA considerable time to analyze and utilize in formulating a proposal for light truck CAFÉ. During this period Sonex plans to achieve multi-cylinder engine operation of the SCS combustion process on U.S. Government sponsored programs. Progress reports and data under government contracts can be made available by coordination with the sponsors. Consequently, the technological risk associated with achieving the full potential fuel economy improvement from the SCRI combustion process will be progressively reduced.

2. <u>What is the technological feasibility and economic practicability of fuel efficiency enhancement based on engine technologies?</u>

   Sonex defines technological feasibility as "a periodic risk determination based on measured performance during technology maturation relative to attaining product expectations". This definition would encourage periodic submission of data to NHSTA as a means to reduce risk and provide confidence in achieving a 25% to 30% improvement in fuel economy. This technological feasibility process would minimize industrial surprises and waiver requests for any candidate technologies that are anticipated to significantly increase fuel economy. Sonex anticipates that once the automotive industry becomes involved with SCS technology, engine developments could be fast paced. This industry has recently been successful in getting world class engines into production on a compressed schedule. For example, the highly successful General Motors/Isuzu Duramax V-8, turbocharged diesel in the Chevrolet Silverado HD and GMC Sierra HD was in production in 37 months. GM also developed and initiated production of a brand new, in-line six-cylinder gasoline engine, the Vortec 4200 for midsize SUVs, in four years by concurrently committing to the development and manufacturing processes. Daimler-Chrysler just announced the formation of a U.S.-based joint venture with Hyundai and Mitsubishi to develop and produce engines. The goal of this new venture, Global Engine Alliance LLC, is to produce 1.5 million engines annually, with production slated to begin in less than two years.

   Given that Sonex combustion technologies for diesel and gasoline engines could be implemented by adapting current production engines, we submit that a three year lead time would not be unreasonable and thus could be aimed at the MY 2006/2007. It should be noted that SCS development work to be performed by Sonex on a pending DoD contract is based on adapting a Subaru automotive gasoline engine to operate on military kerosene-based fuel at higher than stock horsepower levels within nine months of award.

The Sonex commercialization plan is to use this adapted engine as a platform to achieve a laboratory SCS gasoline engine.

Engine and vehicle manufacturers realize the future of their industries depend on making development progress and getting responsive diesel and gasoline engines into the market at competitive advantage. Diesel engines offer the U.S. economy an excellent opportunity for significant fuel savings and in the process a reduction of carbon dioxide emissions associated with global warming. As discussed below, SCS GDI engines have the potential to improve fuel economy by 25% to 30%.

Classical diesel engines run with excess oxygen (run lean), produce high levels of nitric oxide or NO_x and particulate matter (PM). This excess NO_x is a major limitation to broad utilization of diesel engines to enhance fuel economy of U.S. vehicles. However, there is increasing, open discussion by industry executives of the significant potential for greater market share for diesels in the U.S. market. The challenges are to overcome negative buyer perception of the diesel and to meet the more restrictive EPA emissions regulations to be phased-in between 2004 and 2009. Industry executives project that further improvements in light-duty diesel performance, assured durability and fuel price increases will factor into greater market share of diesel-powered light-duty trucks, provided EPA regulations can be met. As recently as March 15, 2002, Dieter Zetsche, Chrysler Group President and CEO, Daimler Chrysler, expressed concern that it would be impractical to meet EPA's light-duty diesel regulations.

European progress in diesel engine technology has been so significant that 40% of all European vehicle production is diesel-powered, including some "top-of-the-line" automobiles. The performance, fuel economy and durability of today's foreign manufactured, turbocharged, common-rail, direct-injected diesels could have significant potential in the U.S. market. However, U.S. and foreign diesel engine manufacturers have not reached a consensus on how best to achieve emissions reductions that will be required in the post 2007 timeframe. The technologies must be cost-effective, durable and require low maintenance. None of the candidates presently being pursued by the industry meet these criteria. The Sonex combustion process as enabled by the SCS piston design could provide a significant design alternative. Development work on a PNGV multi-cylinder diesel engine is the subject of a Sonex proposal being evaluated by the DOE for a potential award in August 2002. This project will encompass both the high compression ratio and low compression ratio modes of the SCS, thus providing a solid basis for comparative evaluation in a state-of-the-art engine.

The economic practicability of the SCS in a second generation of GDI engines in the 2006 timeframe is very high when viewed from the perspective of solving the first generation GDI engine NO_x problem. Mitsubishi has produced more than 1 million vehicles since 1996 powered by GDI engines having displacements from 1.1 to 4.5 liters. Volkswagen has introduced GDI engines and expects to transition all of its European market vehicles to this engine technology within 5 to 7 years. No U.S. manufacturer has this level of experience with GDI engine development or production.

The DOE has tested a Mitsubishi, 5-passenger sedan in the 2,700 pound class (Ford Focus and Volvo S40) and measured 53 mpg[1]. The DOE testing demonstrates the significant GDI engine NO_x problem that has precluded introduction of these vehicles in the U.S. due to high sulfur levels in domestic gasoline, which precludes the use of NO_x traps. Low sulfur gasoline is available in Japan and some European countries.

The U.S. introduction of low sulfur gasoline (30 ppm) in 2006 may not enable aftertreatment using a NO_x trap as a means for first generation GDI engines to meet EPA NO_x regulations. Application of a NO_x trap involves periodic controlled rich excursions in the exhaust flow through over-fueling. In today's GDI engines this "spike" of richer operation (to allow the NO_x trap chemistry to disassociate the nitrogen and oxygen) is controlled by retarding spark, adjusting fuel injection timing and other engine controls, depending on the design features of the engine. The control system typically cycles through the NO_x reduction by enrichment on 50-second intervals and results in a 2% or greater loss of fuel economy.[2] A NO_x trap may not be adequate for today's spark-ignited direct injection gasoline engines as the trap may need to operate at 90% conversion efficiency.[3] In Toyota's June 12, 1998 comments to the EPA on the draft Tier II regulations, they indicated the NO_x conversion rate in the trap could not be sustained above 80% if sulfur content exceeded 30 ppm. Also, the current state-of-the-art NO_x traps degrade over time and thereby reduce the margin of performance specified in EPA regulations.

The SCS at this stage of development demonstrates an 80% lower engine out NO_x level than the Mitsubishi GDI engine. This low NO_x level will be an excellent match (if needed) to a NO_x trap that may degrade to a 70% to 80% conversion efficiency range. It should be noted that the SCS already exhibits an engine out NO_x level that is approximately 85% lower than the Northern Virginia tailpipe criteria for Washington, D.C. area pollution control.

3. <u>What is the cost effectiveness of each technology identified in question 2, assuming alternative, plausible fuel prices forecast for MY 2005-12010, and assuming alternative payback periods ranging from 3 years to 10 years?</u>

In estimating the cost-effectiveness of the SCS as it would be applied to a GDI engine, Sonex makes the following assumptions in its response to this question:

(1) The vehicle is operated 15,000 miles every year and has a baseline fuel economy of 20 miles per gallon. Fuel price increases do not reduce use.

(2) Fuel price increases 20 cents per gallon each year from a baseline of $1.50 per gallon.

(3) The SCS GDI engine improves fuel economy by 25%.

(4) The payback potential is measured over 5 years or sooner during which the vehicle is paid for and still has a useful life.

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2 F. Zhao et al, "Progress in Energy and Combustion Science", vol. 25 (1999), pp 437-562.

3 M.S. Brogan et al, "Recent Progress in NOx Trap Technology", SAE Paper 980933, 1998.

Sonex proposes two possible product introduction scenarios for the SCS GDI engine. The first assumes vehicles have been in production using a form of the first generation GDI engine and a NO_x trap to provide a 12.5% improvement in fuel economy. The SCS is phased in with a cost increase of $150 associated with the unique pistons (6 cylinder engine, $25 increase per piston). Therefore, the additional fuel economy improvement of 12.5% is the basis of the recovery of the $150 increased cost of the SCS pistons. This is obtained early in the second year of vehicle operation.

The second and more likely scenario assumes the SCS is introduced as an enabling technology for a second (or third) generation of GDI engine wherein a $1,300 cost increase includes the fuel injection system in its entirety, the SCS pistons, and a NO_x trap. We assume the fuel delivery system has a cost increase of $1,000 (over a baseline manifold injection system), the pistons cost $150 more, and a NO_x trap costs $150. The 25% improvement in fuel economy achieves payback in the fourth year.

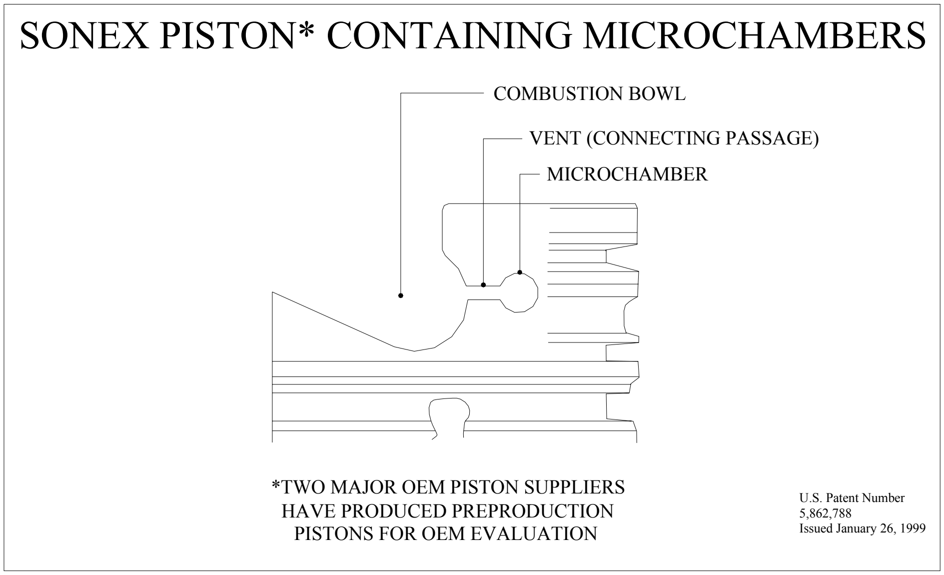


Figure 1

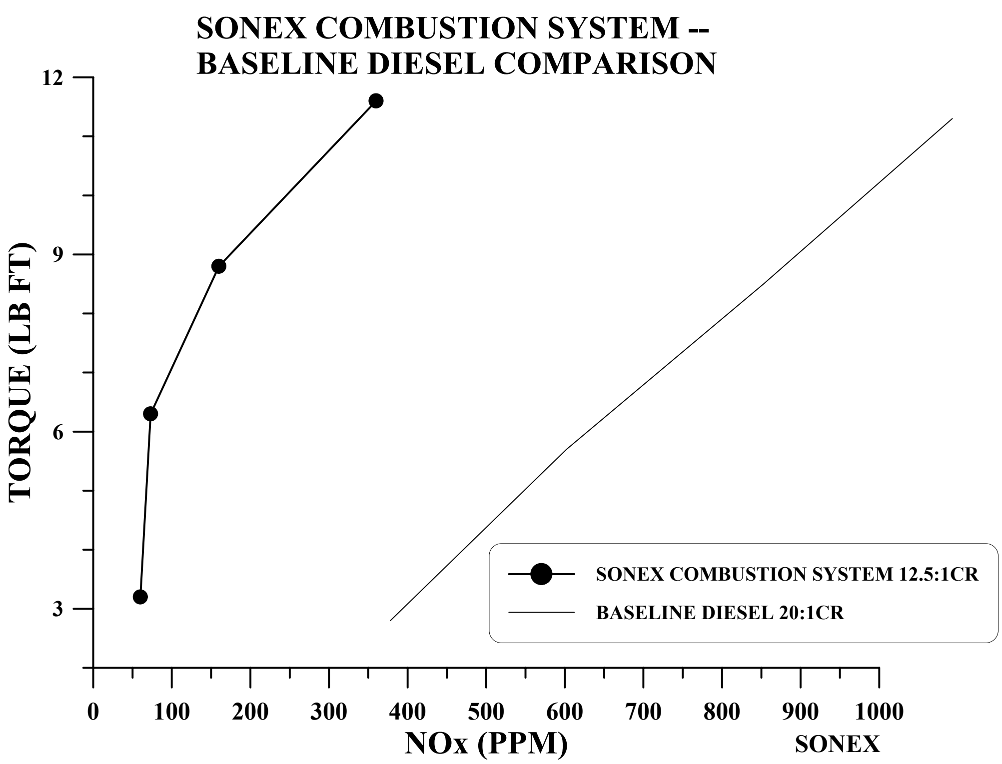


Figure 2

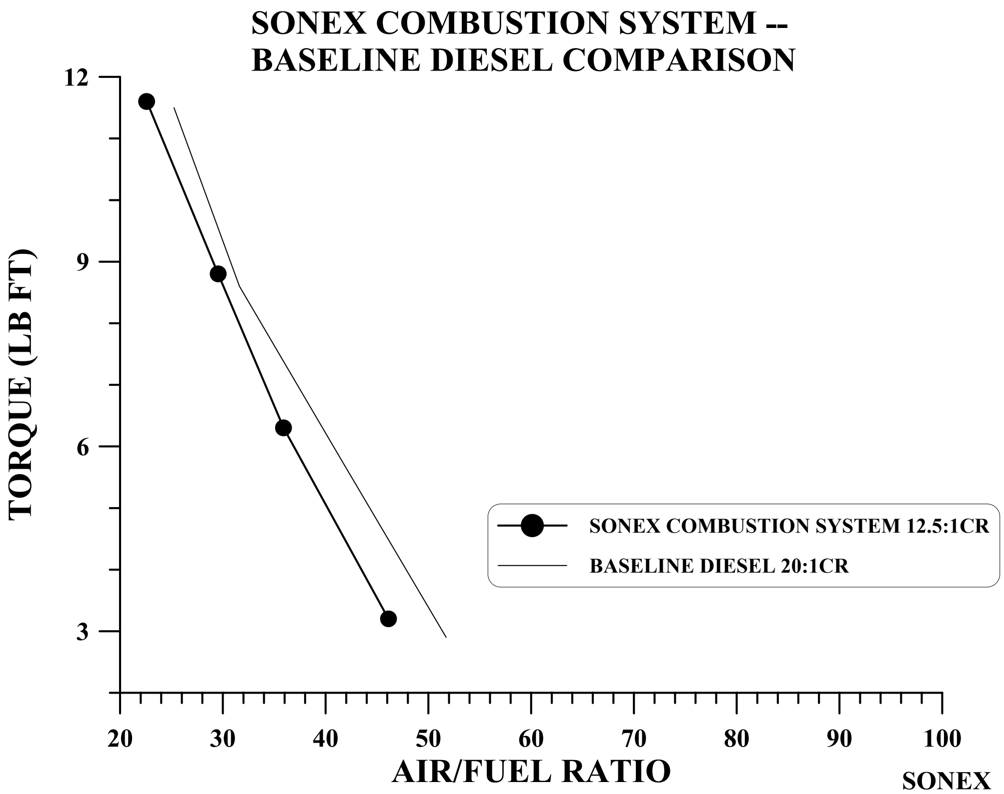
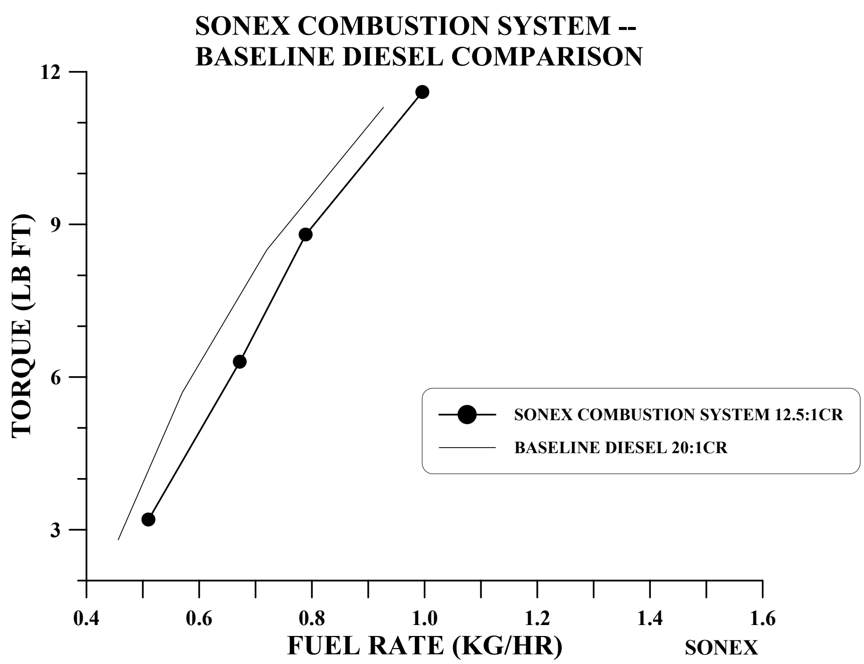


Figure 3



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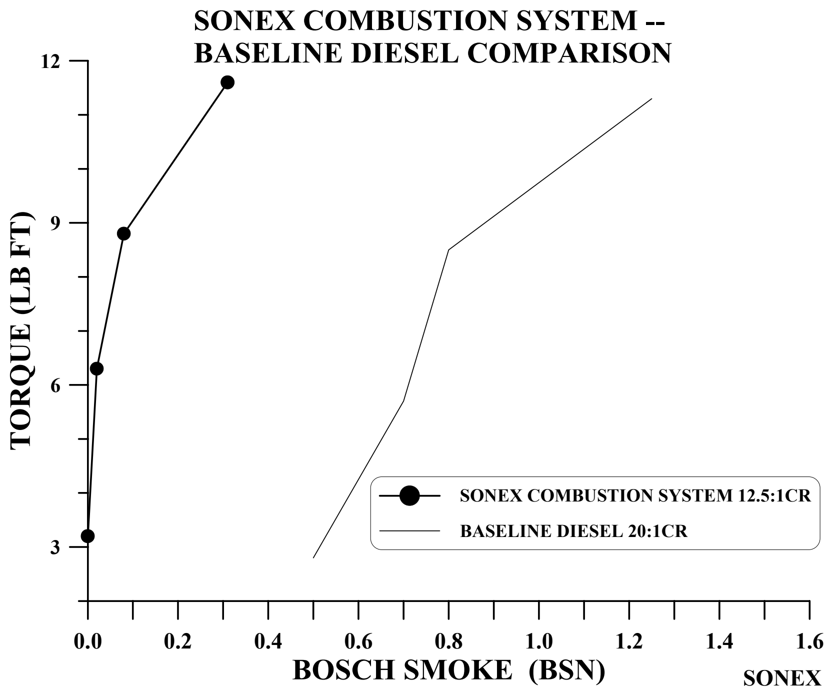


Figure 5

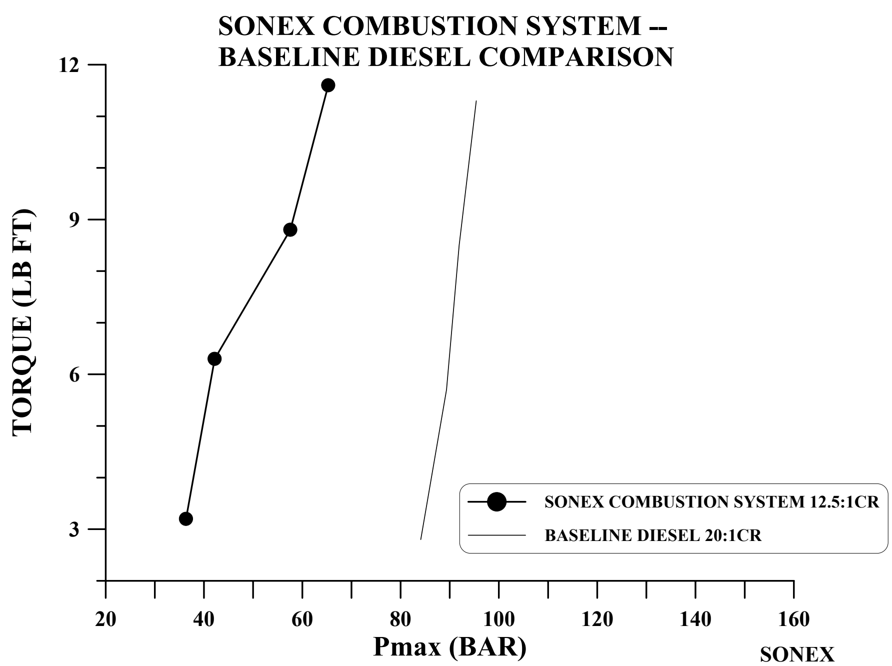
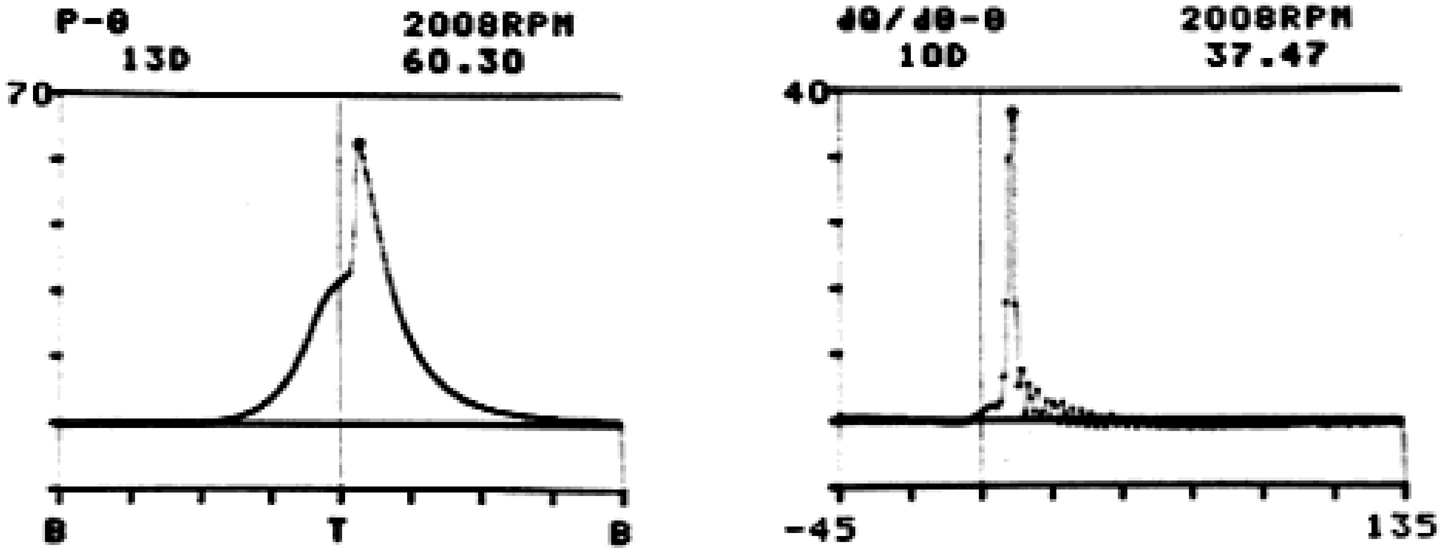
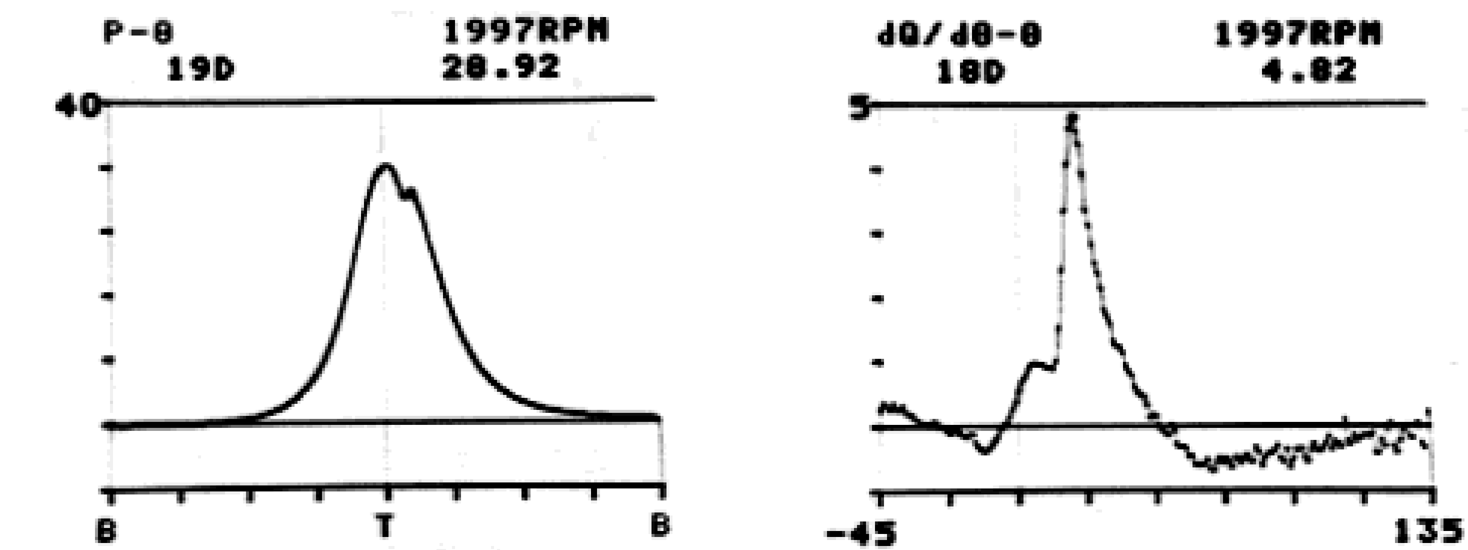


Figure 6



Full Load, with EGR, CR = 12.5:1, D2 Diesel, Mechanical Injection@ -20degrees

Figure 7



Quarter Load, with EGR, CR = 12.5:1, D2 Diesel, Mechanical Injection@ -20degrees

Figure 8